The cluster structure in light neutron-rich nuclei

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outline

Introduction

The cluster structure of ^{12}Be

Research plan at RIKEN

What is cluster?

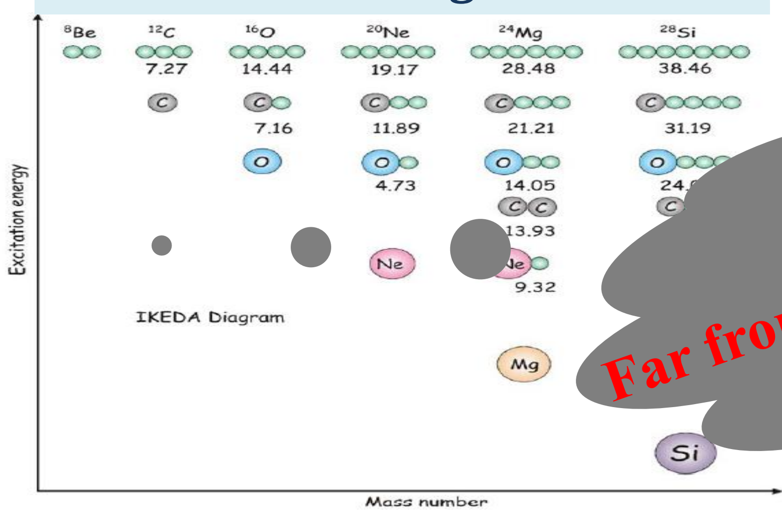
Objects congregate into clusters on all physical scales.

(Universe)

(Life)

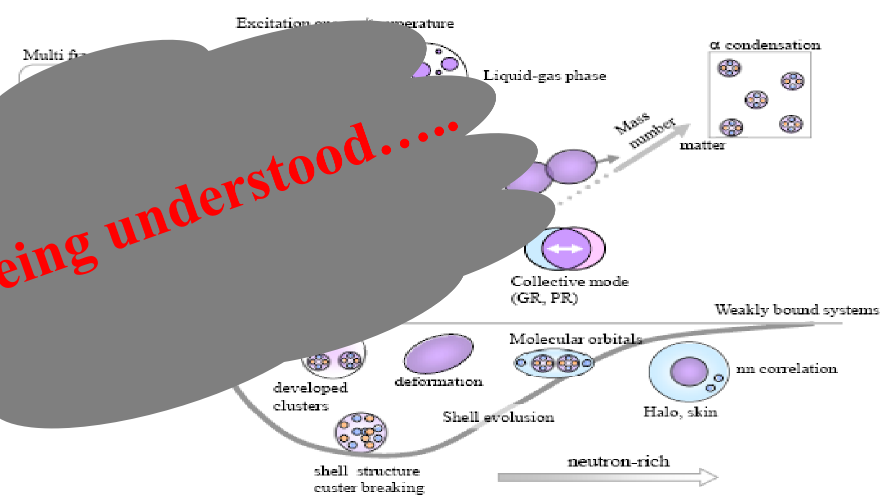
Nucleon Clustering in nuclei

stable even-even nuclei : Ikeda diagram



K. Ikeda, et al., PTPS, E464(1968)

Neutron-rich nuclei : Molecular structures, Dineutron



Far from being understood.....

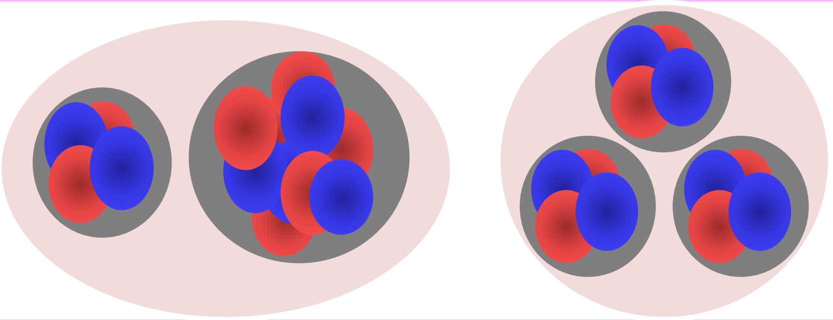
Y. Kanada-Enyo, et al., PTEP1, 01A202(2012)

α-Clusters in Nuclei

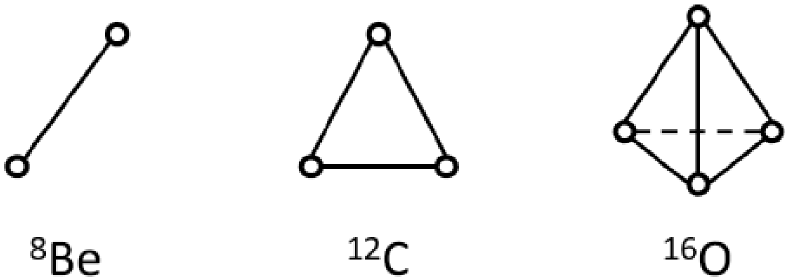
The Hoyle state of ^{12}C with the 3-α structure.

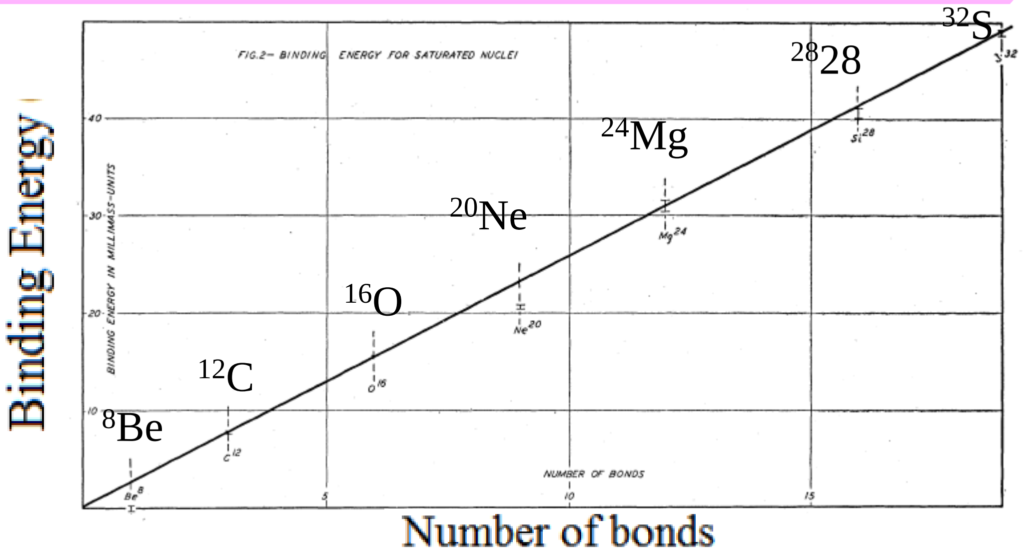
- 0^+_3 (12.05 MeV) in ^{16}O (α + ^{12}C)
- 4^+(10.15 MeV) in ^{10}Be (α + ^{6}He)

PRL96(06)042501



α-Cluster model of Hafstad and Teller for α-conjugate nuclei (~1930s).

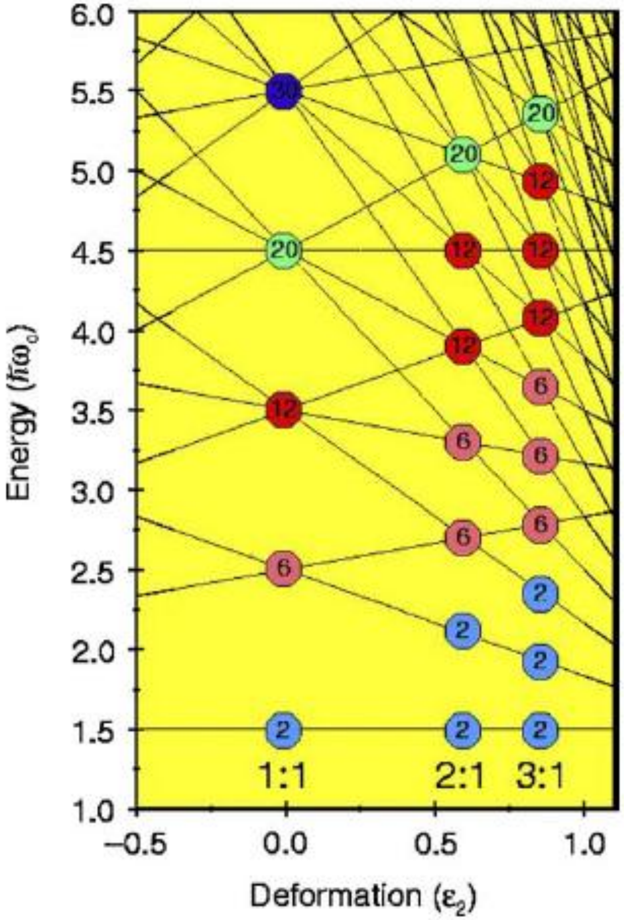


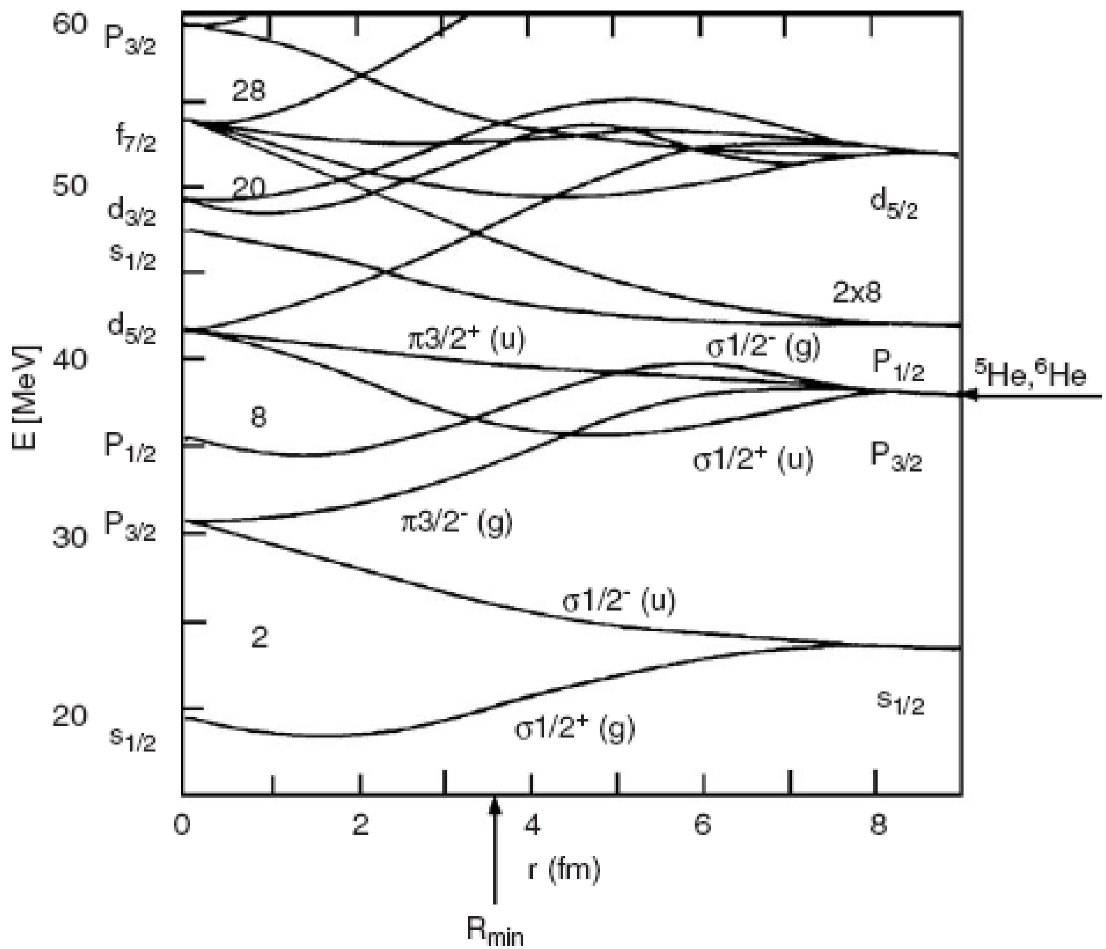


(p,p α) experiments on ^{6,7}Li, ^{9}Be, ^{12}C, ^{40}Ca: large α spectroscopic factor .

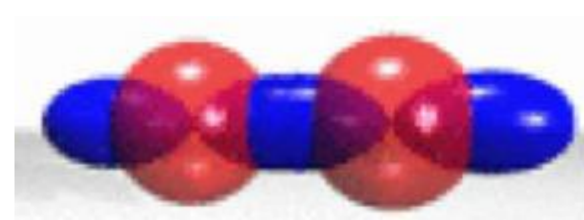
α-decay (preformation of α-clusters?)

- **Many theoretical models**: GTCM, AMD, FMD, GCM, THSR……
- Earlier two-center models, e.g. TCSM, TCHO



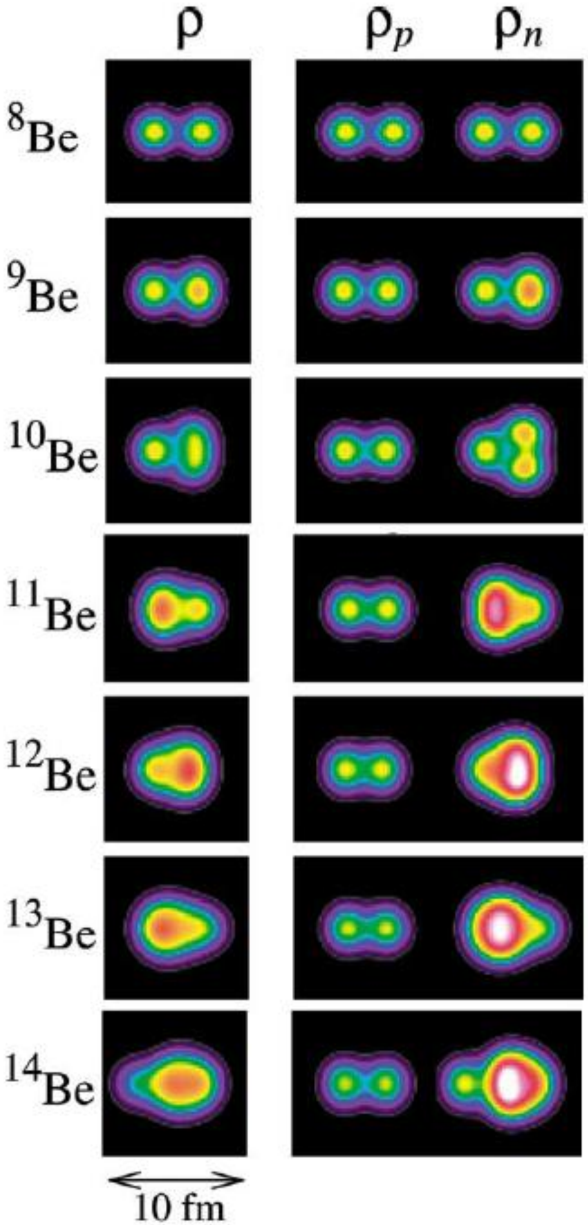


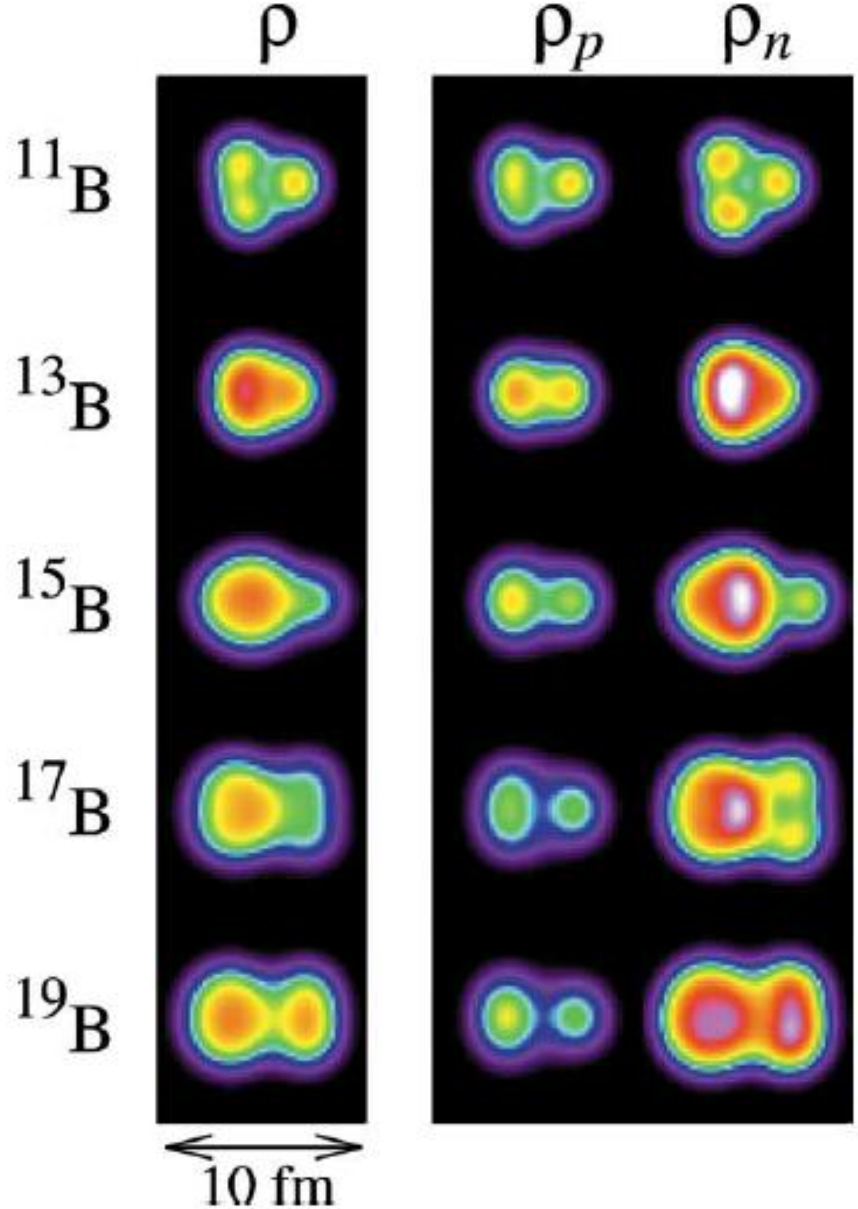
Phy.Rep432(06)43
C. R. Physique 4 (2003) 475.
Z. Physik A 357 (1997) 355

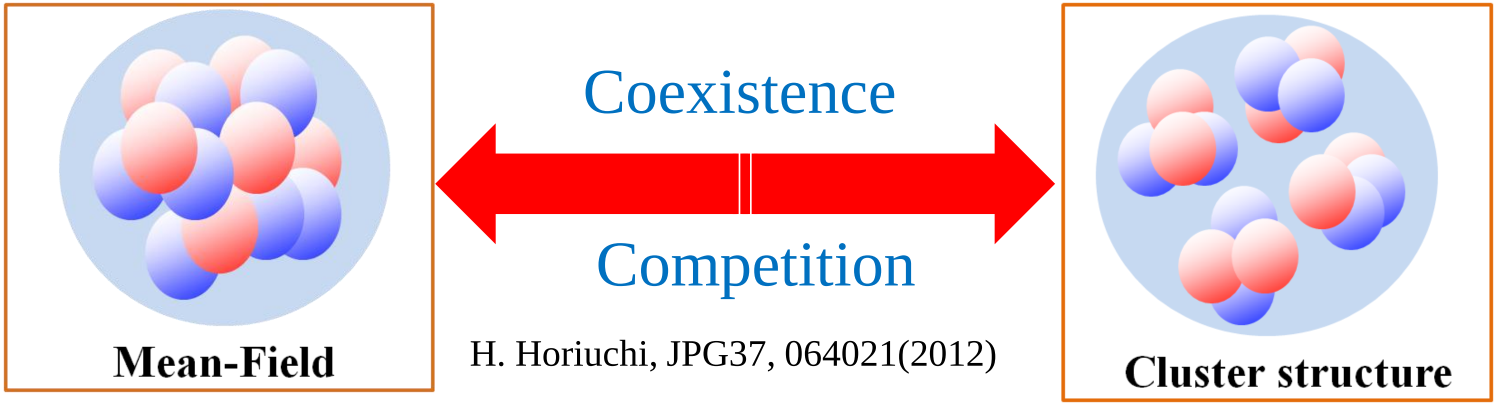


- **Anti-symmetrized Molecular Dynamics (AMD)** calculations

➢ No assumptions on the preformation of clusters. C.R. Phys. 4(03)497





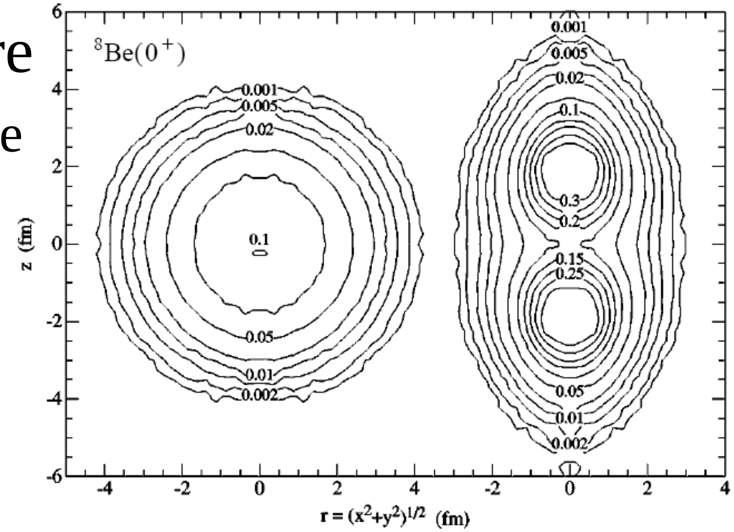


H. Horiuchi, JPG37, 064021(2012)

Mean-field theories could not reproduce the cluster structure.

- Ab initio Calculation of ^{8}Be : α+α structure
- ➢ Variational Monte Carlo with realistic nuclear force

  [PRC62(00)014001]



Duality of nuclear wave functions (WF): mean field + cluster

- e.g. closed-shell WF of ^{16}O(g.s.) is equivalent to ^{12}C+ α cluster WF.

T.Yamada, PTP120(08)1139; H.Horiuchi, PTPS192(2012)1

- **The mechanism of cluster formation is far from settled.**

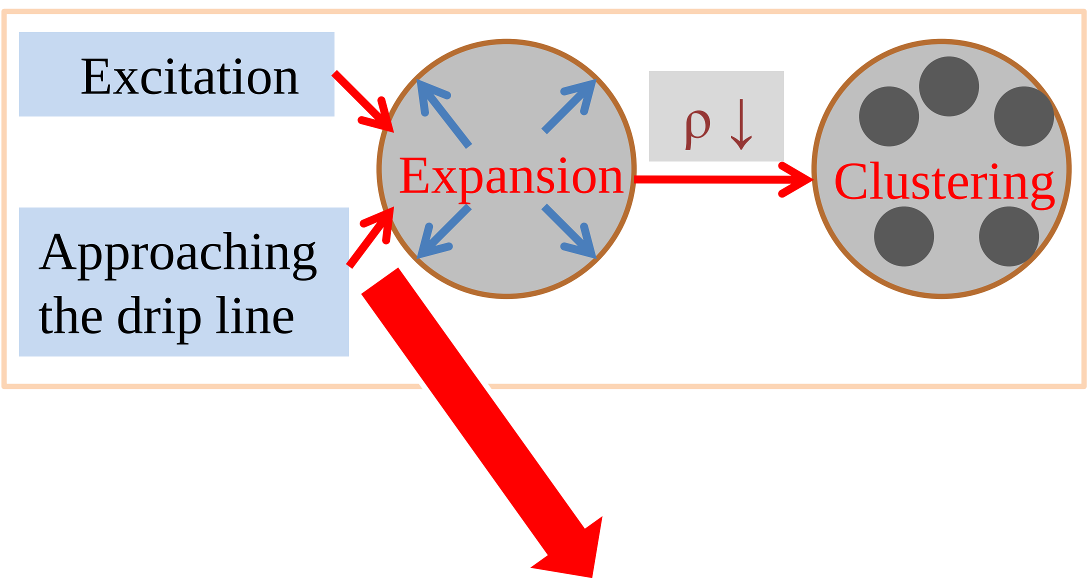
➢ "Clusters of wave functions" + "binding".

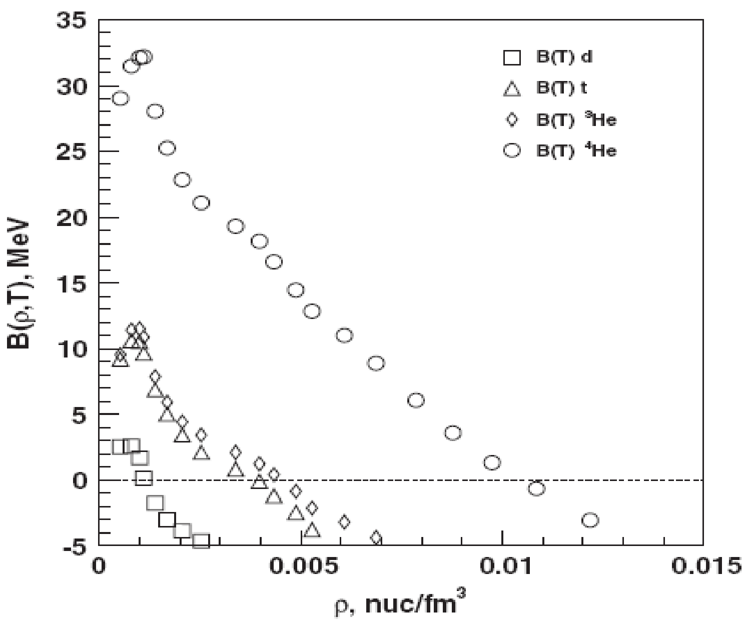
➢ May be attributed to accumulation of the "**relative tightness**" of local clusters, stemming from the decrease of environmental matter density.

➢ Measurements in heavy ion collisions.

K. Ikeda, PTPS, E464(1968)

K. Hagel, PRL108(2012) 062702





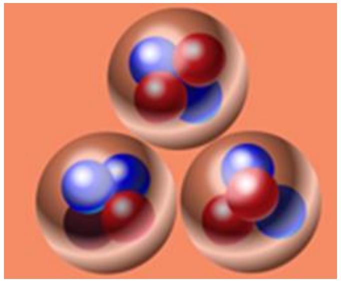
Systematic measurements in neutron-rich nuclei needed.

Nuclear clusters in astrophysics

Key role in nucleosynthesis processes

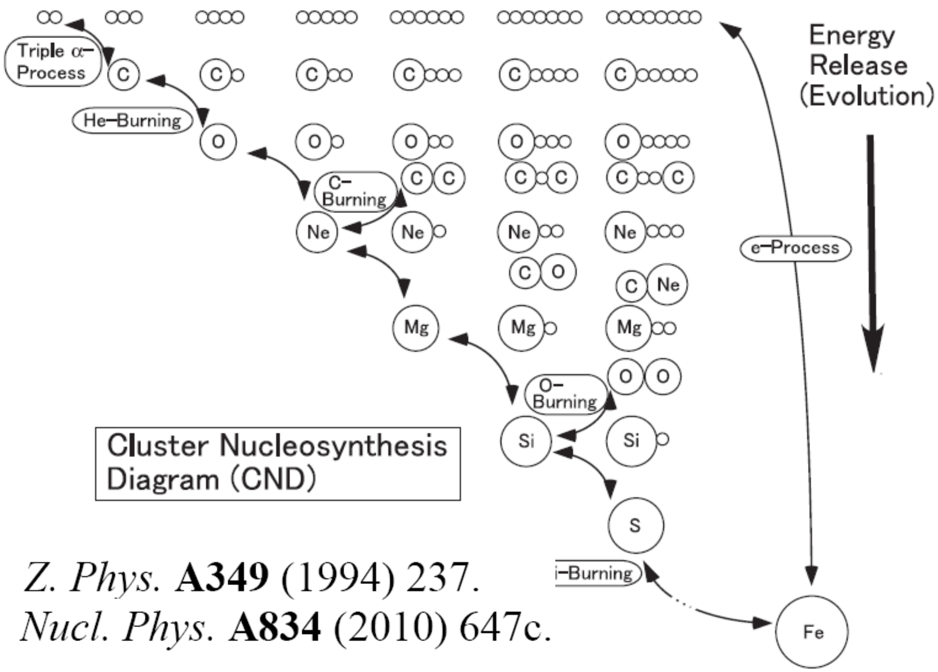
>e.g. the Hoyle state in ^{12}C

>Cluster Nucleosynthesis Diagram (S. Kubono)

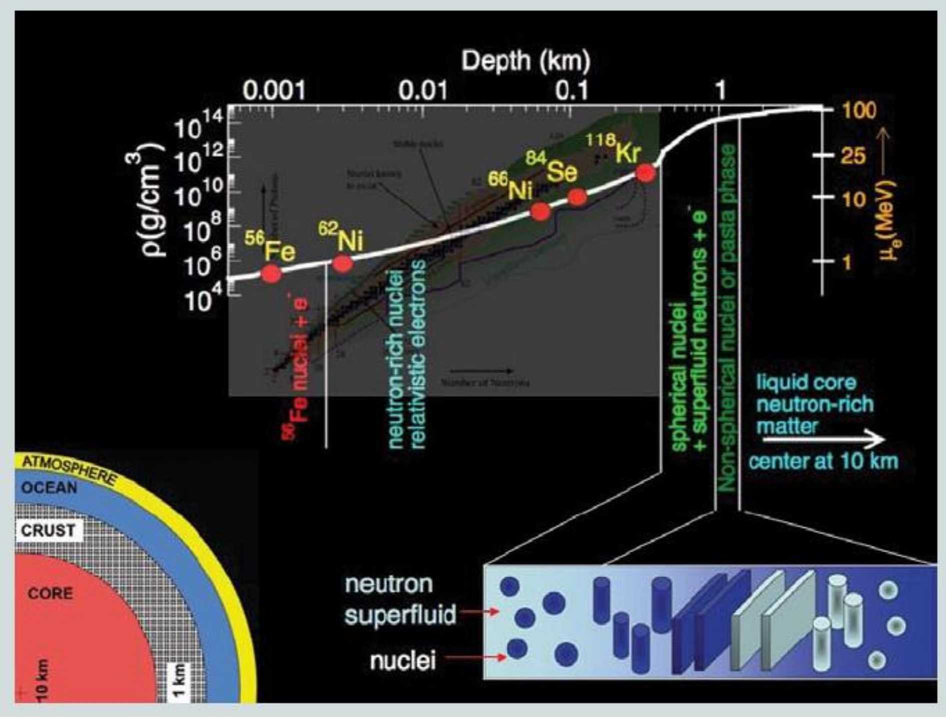


Nuclear clusters in the outer crust of neutron star

(Sience304(04)536)



Z. Phys. **A349** (1994) 237.
Nucl. Phys. **A834** (2010) 647c.

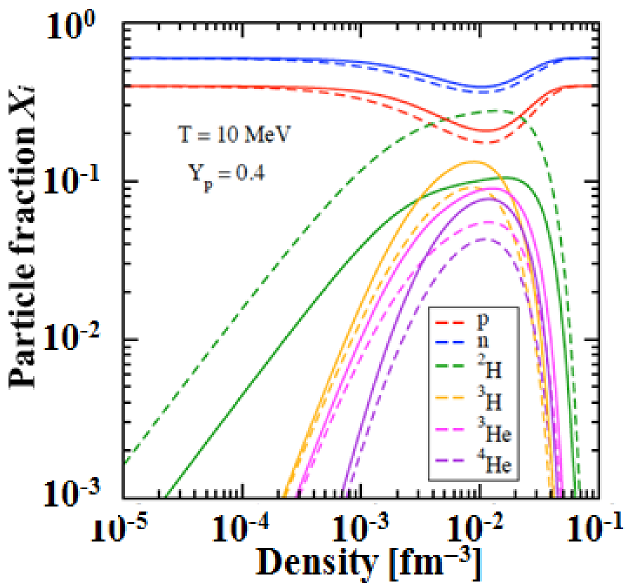


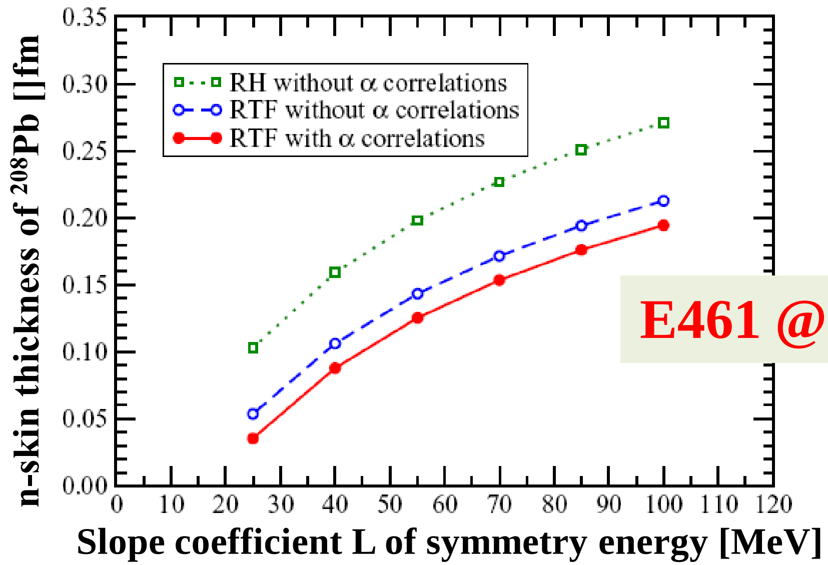
Cluster correlation in nuclear matter (EOS)

Generalized relativistic density functional theory (gRDF)

>Consistent description of nucleon and cluster [PRC 81(2010) 015803, 89(2014) 064321]

>Clustering occurs at ρ=0.001− 0.03 fm^{-3} (nuclear matter and finite nuclei)





E461 @ RCNP

Cluster-correlation in nuclear matter

gRDF

Cluster in the surface of heavier nuclei

Nuclear equation of state (EOS)

Neutron-skin thickness

e.g. ^{208}Pb, ^{132}Sn

Experimental investigations of cluster states

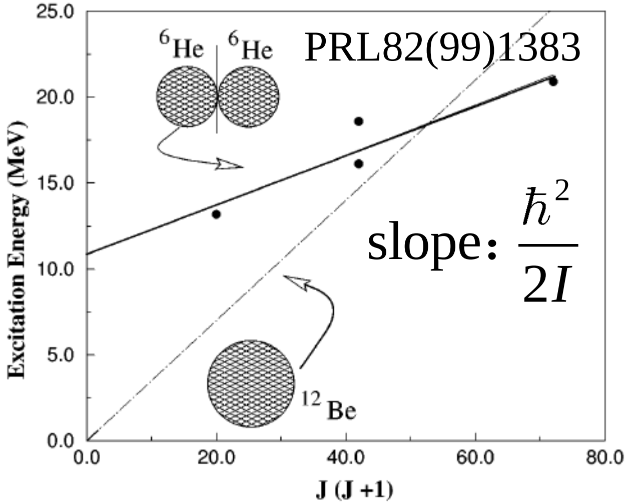
- **Cluster structure in the excited states:**

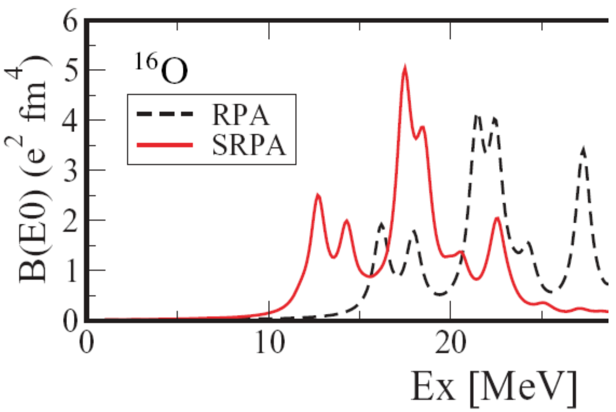
➢ Inelastic scattering/transfer/resonant scattering+invariant mass
[e.g. ^{12}Be(*PRL112(14)162501*), ^{10}Be(PRL96(06)042501)]

➢ E_x~spin systematics (rotational band) → large deformation

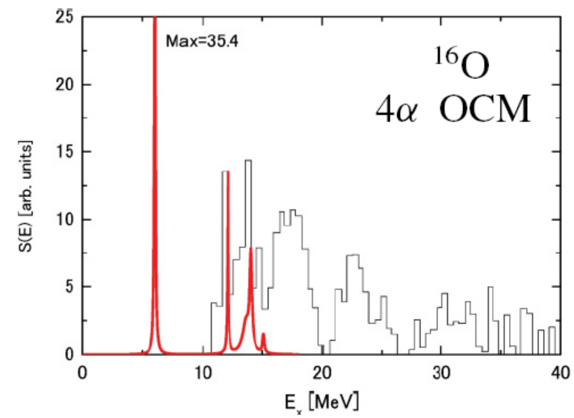
➢ Dominant cluster decay → large Cluster Spectroscopic Factor

➢ Charasteristic transition strength(Monopole transition: sensitive probe)





PTP120(08)1139, PRC 85(12)034315



PRC83(11)044319

- **Very Challenging to make conclusive identification**

➢ ^{12}C (0^+_2), ^{16}O(0^+_2 and 0^+_3), ^{20}Ne (0^+_4)

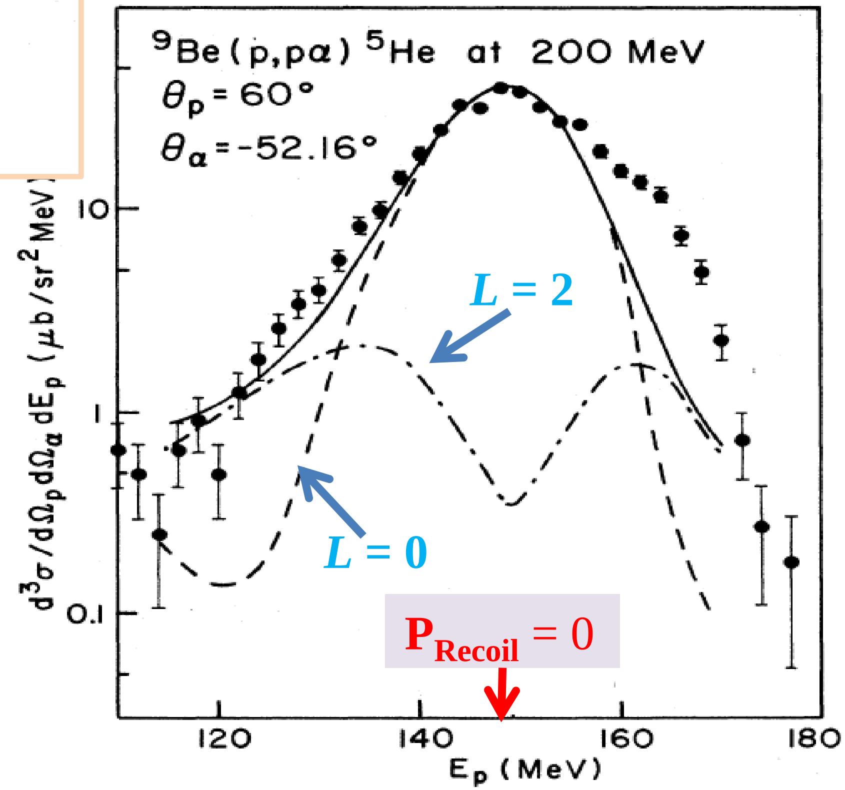
➢ ^{12}Be (0_3^+),^{10}Be(4^+)

- **Cluster structure in the ground state:**
  - Quasi-free cluster knock out (100 ~300MeV/u)
  - $^{6,7}Li$,^{9}Be,^{12}C [PRC15(77)69]
  - α-cluster spectroscopic factor extracted with DWIA calculations

Matrix element (from DWIA calculations)

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p} = S_\alpha F_k \sum_\lambda |T^{L\lambda}|^2 \frac{d^3\sigma}{d\Omega_{p-\alpha}}$$

Free p-α elastic cross section



A. Nadasen, et al., PRC40, 1130 (1989)

outline

Introduction

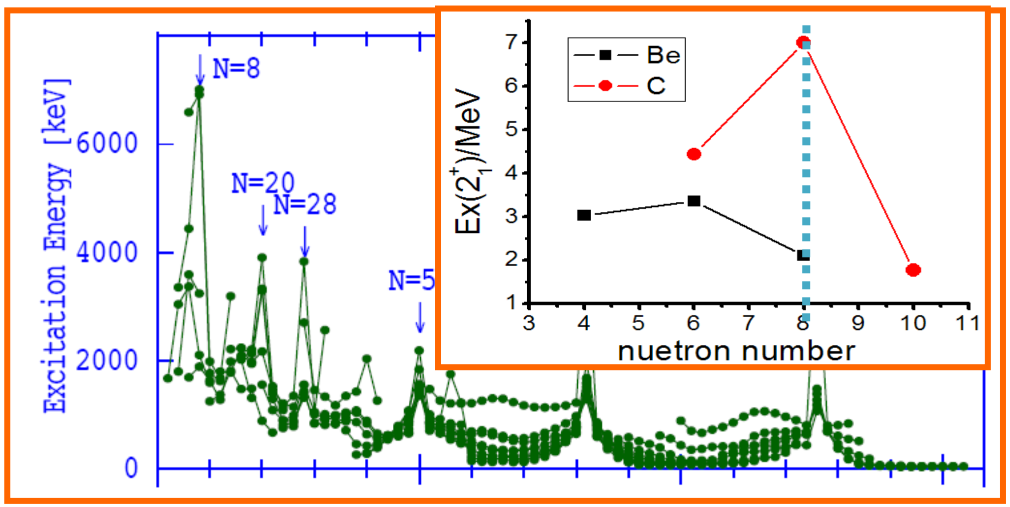
The cluster structure of ^{12}Be

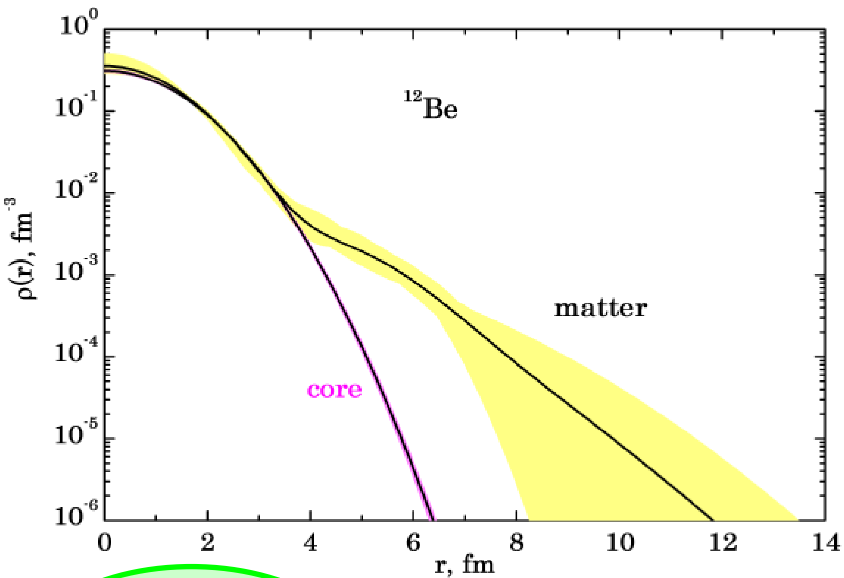
Research plan at RIKEN

Uniqueness of ^{12}Be in cluster physics

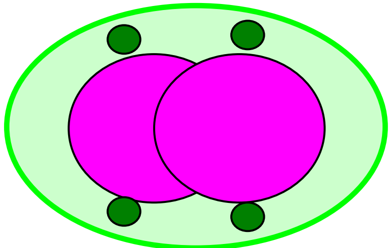
- **Breakup of the *N* = 8 magic number**
  - Decrease of $E_x(2_1^+)$
  - Matter density distribution with long tail
  - Reduction of β-decay strength (to ^{12}B)
  - Ground state Spectroscopic Factors measurements: Intruder state.

PRC50(94)1355
NPA875(12)8
PRL85(00)266
PRL96(06)032502



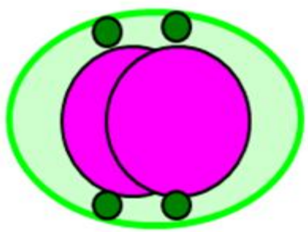


- **α-4n-α cluster structure?**
  - ^{12}Be(g.s.): Dominant $(\pi_{3/2}^-)^2(\sigma_{1/2}^+)^2$

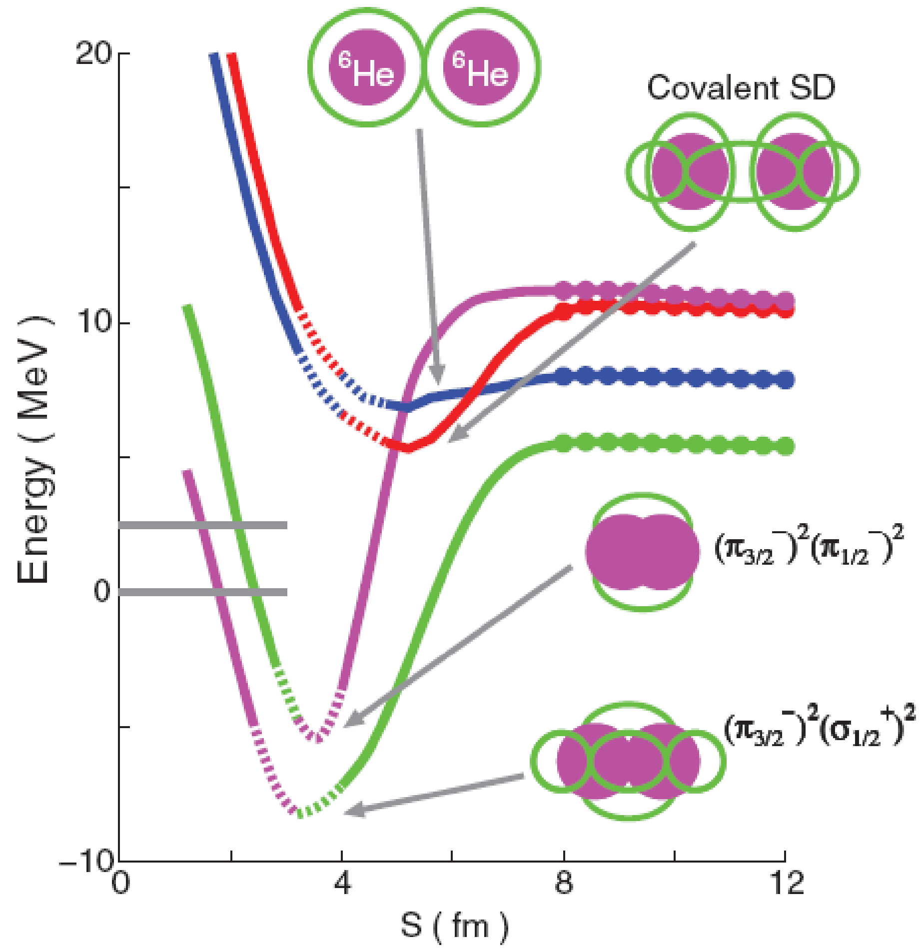


PRL100(2008)182502
PRC85(12)014302

- **Rich cluster structures predicted by GTCM calculations**
  - “Covalatly” binding (MO) configurations for low-lying states.
  - Molecular Resonance (MR) states above particle emission threshold.



M. Ito, et al.
PRL100(2008)182502
PRC85(12)014302
PRC85(12)044308



- **AMD and GCM calculations**

PRC68(03)014319, NPA836(10)242

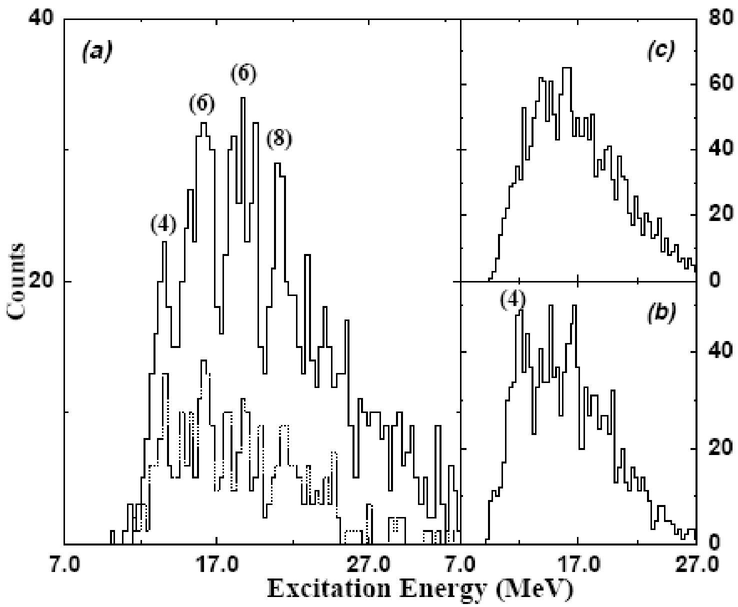
Studies on the cluster structure of ^{12}Be

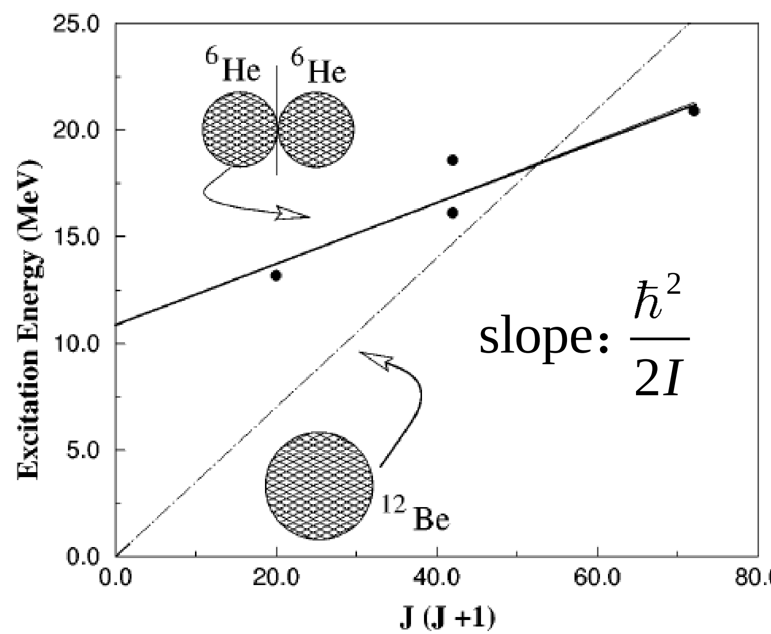
- **Inelastic scattering** (Korsheninnikov) :hints of ~10 MeV cluster state
- **2-n or 3-n transfer** (W. Von Oertzen) : high-lying excited states

PLB 343(95)53 IJMPE 10(08)2067

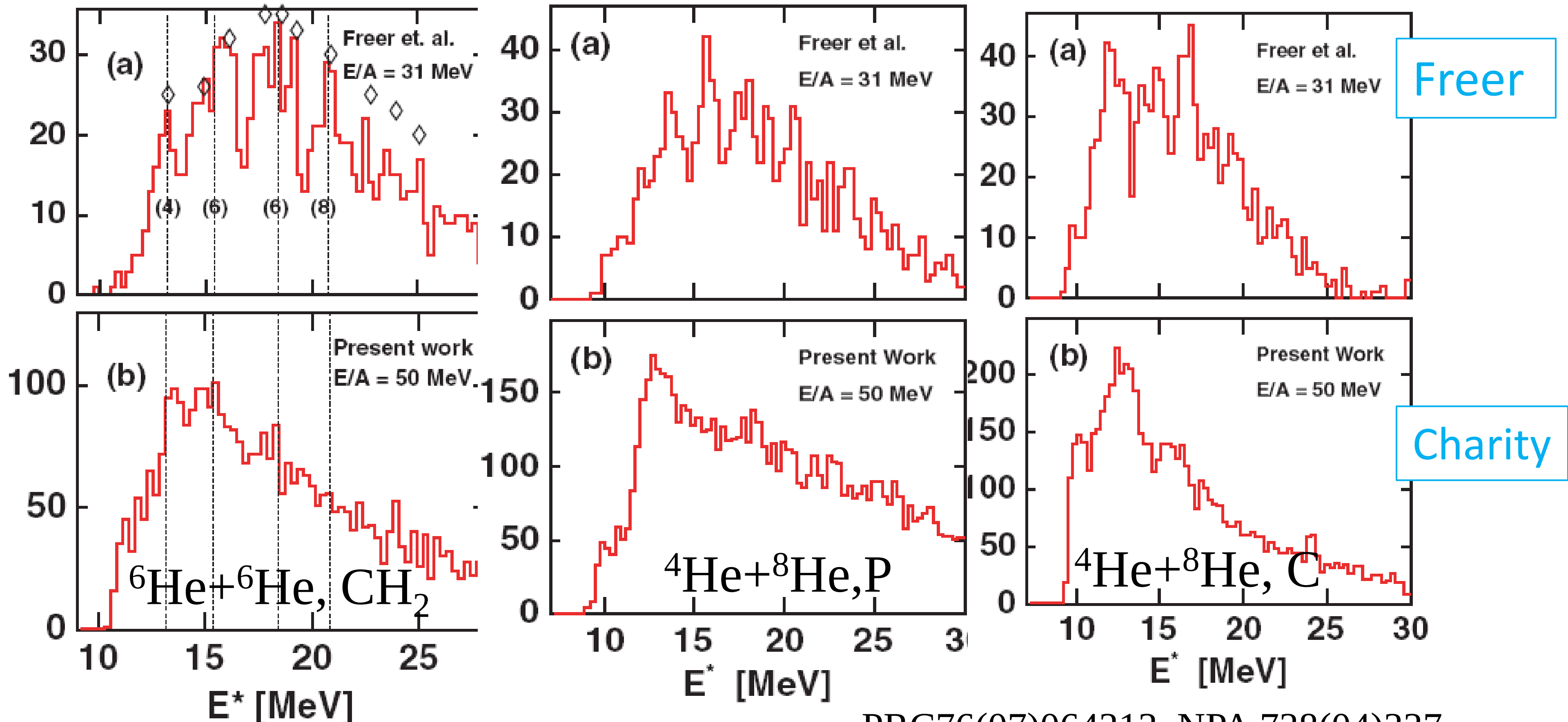
- **Inelastic breakup & measurements of the fragments** (Freer et al.)

➢ A rotational band observed with large deformation, in accordance with the cluster struture. [*PRL82(99)383*]





- **Inelastic breakup & measurements of the fragments** (Charity et al)
  - ➢ Most of the resonances observed by Freer were not reproduced. (50AMeV)

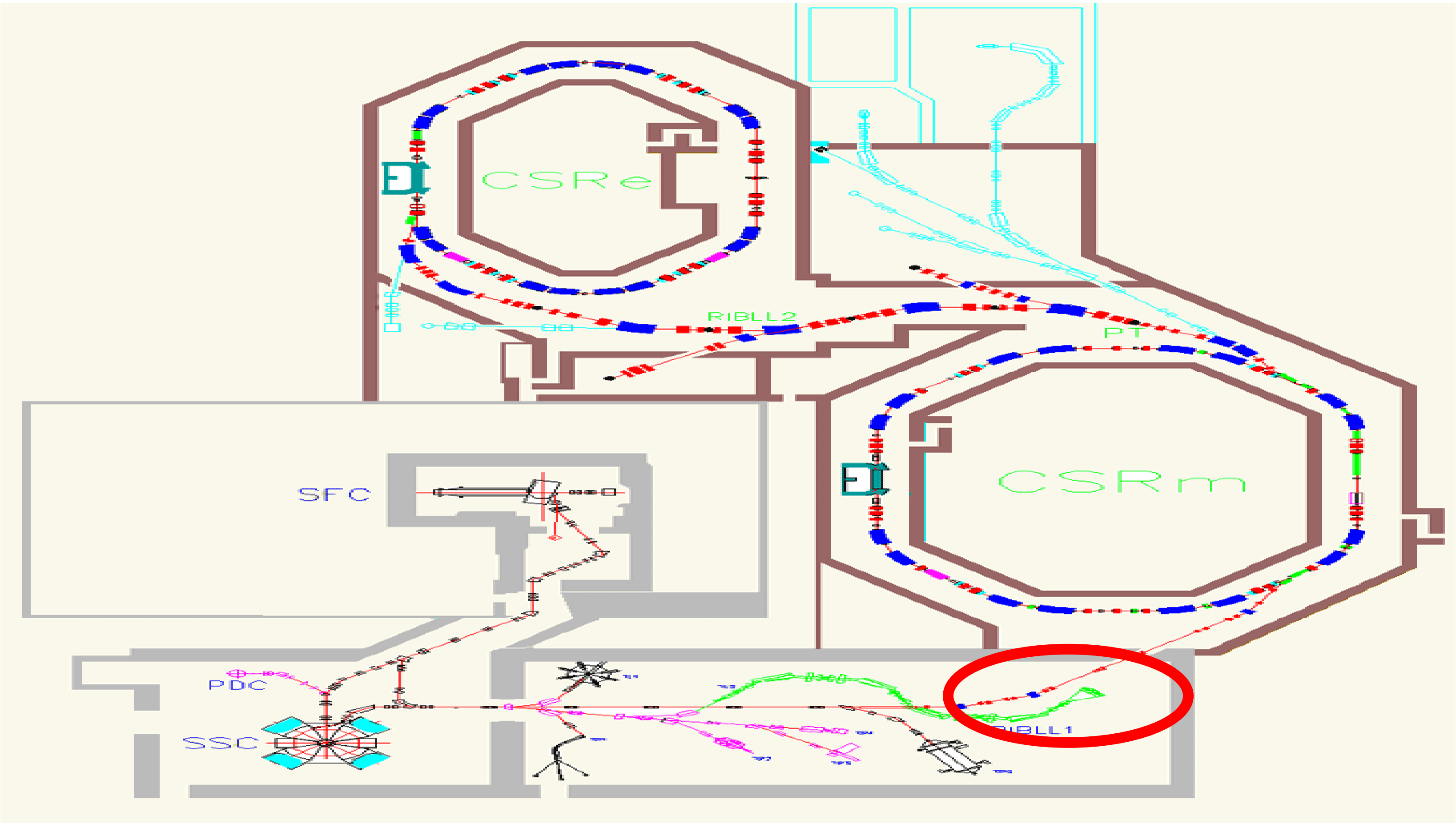


PRC76(07)064313, NPA 738(04)337

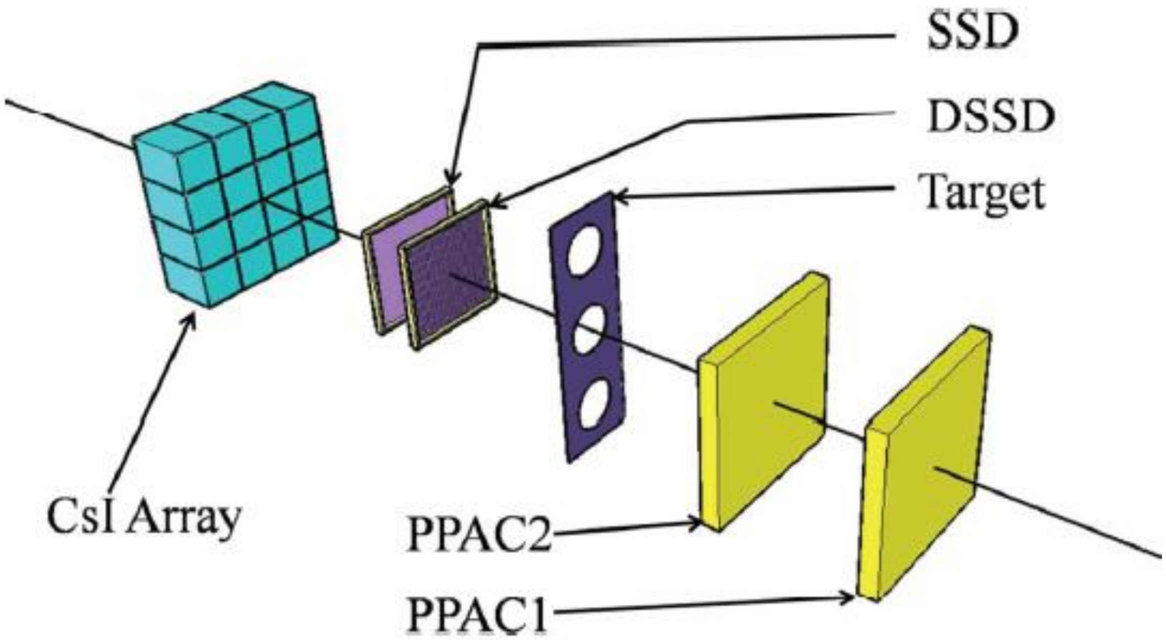
- **Inelastic breakup & measurements of the fragments** (Saito et al.)
  - ➢ Similar to Charity's: dominant by non-resoant background. (60AMeV)
- **Enhancement of non-resoant process suggested by AMD.**

PRC63(01)034615

RIBLL1@HIRFL,Lanzhou, China

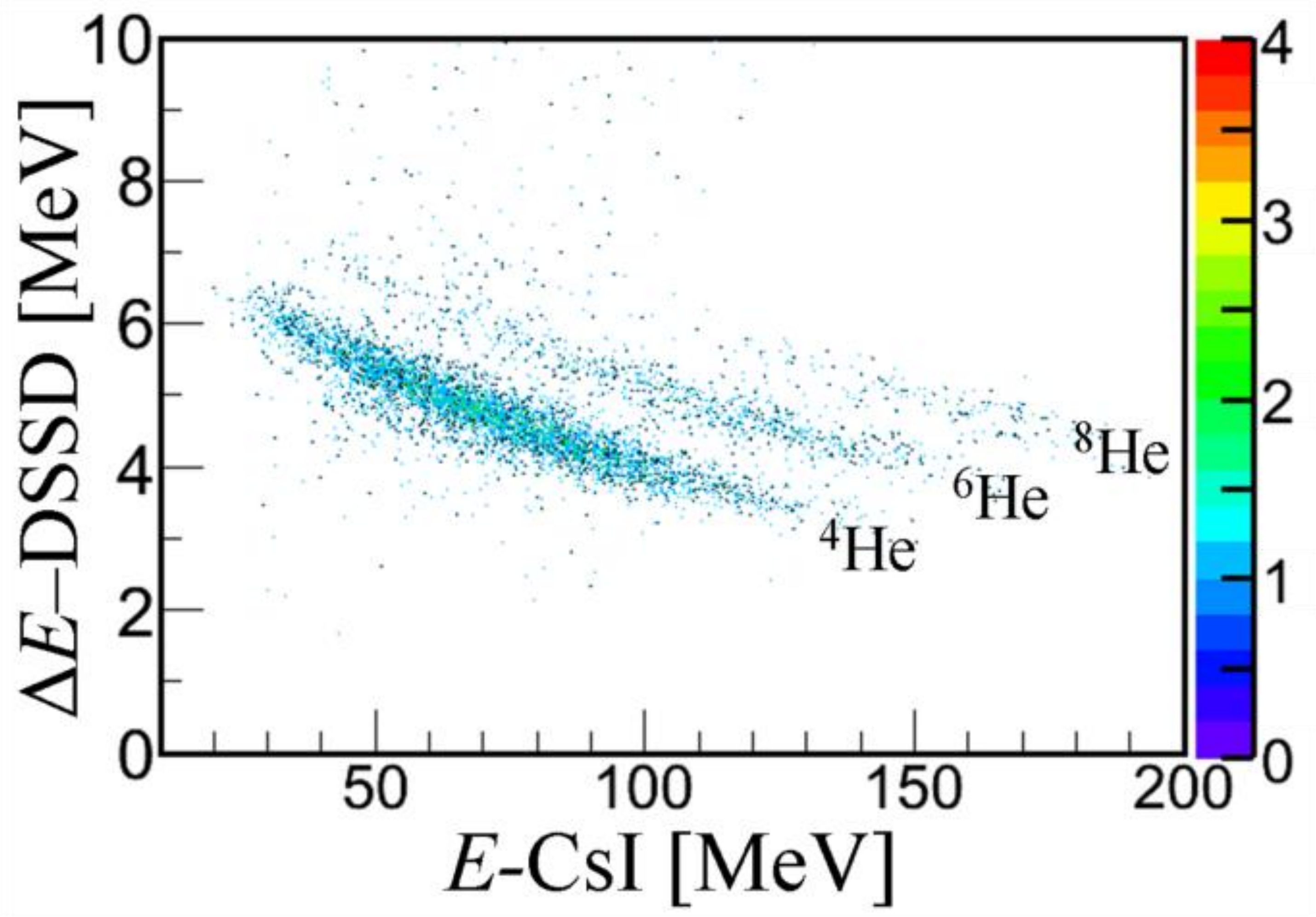


Experimental Setup

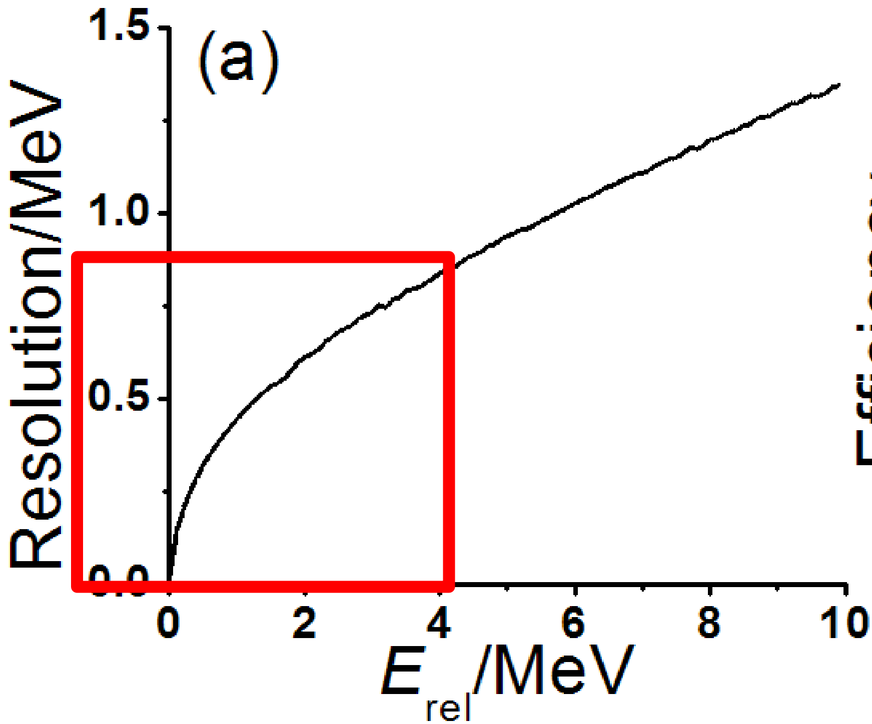


Beam： ^{12}Be， 29 MeV/u， ~3000pps
Target： Carbon, 100 mg/cm^2
DSSD： 32 2mm-stip,300μm ,
CsI： 2.5cm*2.5cm*3cm,
Detection focused on the most forward angles (0º~12º)
Multiplicity-2 events for cluster decay!

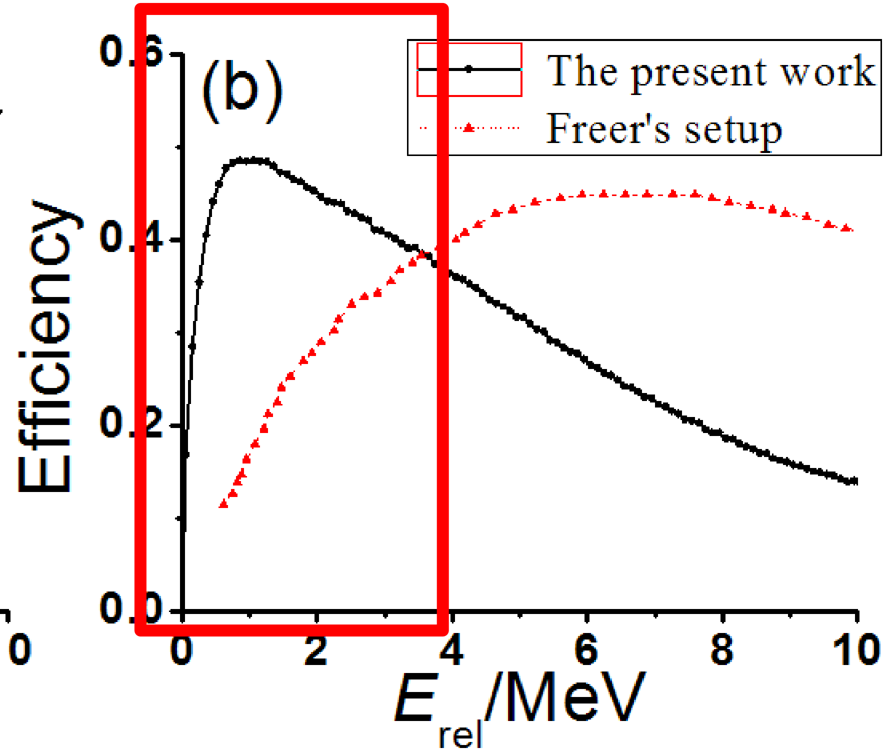
Particle Identification of Fragments



E_{rel} resolution



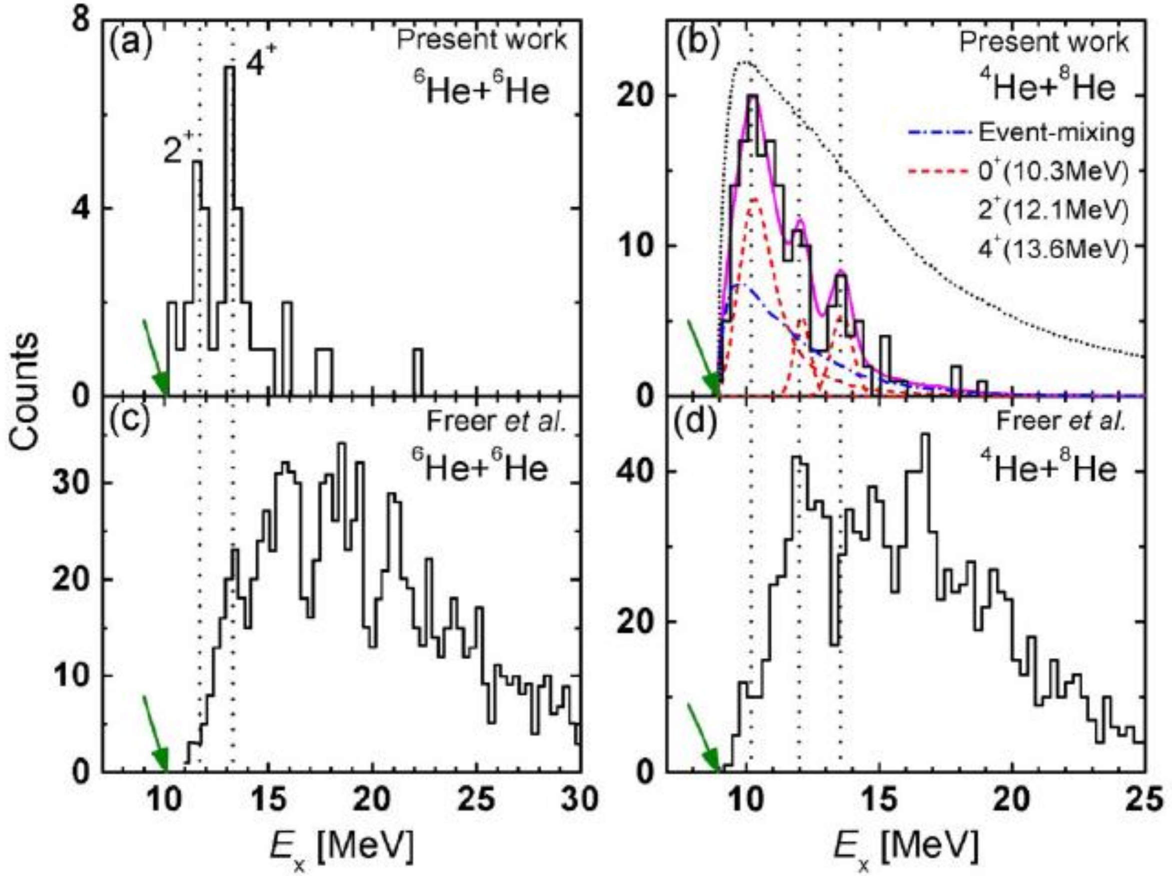
Detection effeciency



Resolution is below 1 MeV, which is mainly limited by the target thickness .

Our setup is much in favor of the low E_{rel} detection in comparison to that of Freer's experiment.

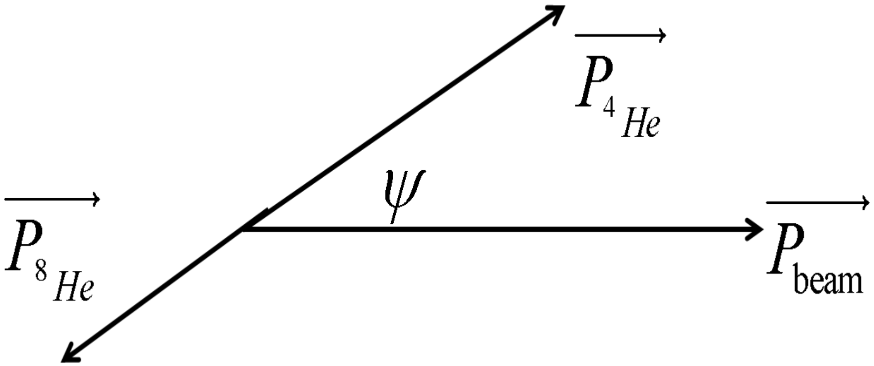
Excitation Energy Spectrum of ^{12}Be

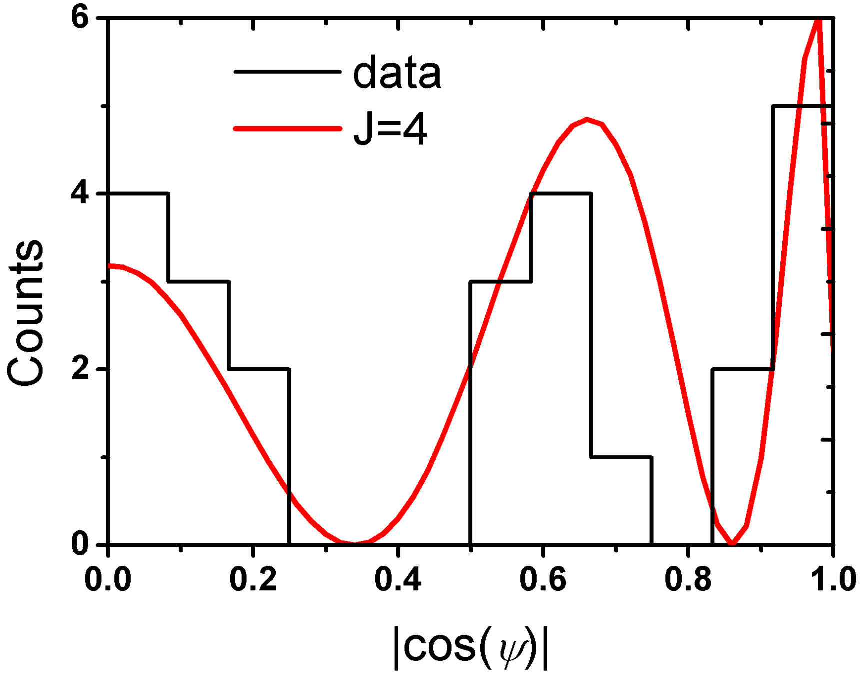


The (total) width of the 10.3 MeV state is determined to be 1.5(2) MeV, which agrees well with the GTCM calculation. PRC84(11)014608

- **AMD**: larger width for the band-head than for other higher spin members of the ^{6}He+^{6}He band. PRC68(03)014319

Angular correlation analysis for 13.6MeV state

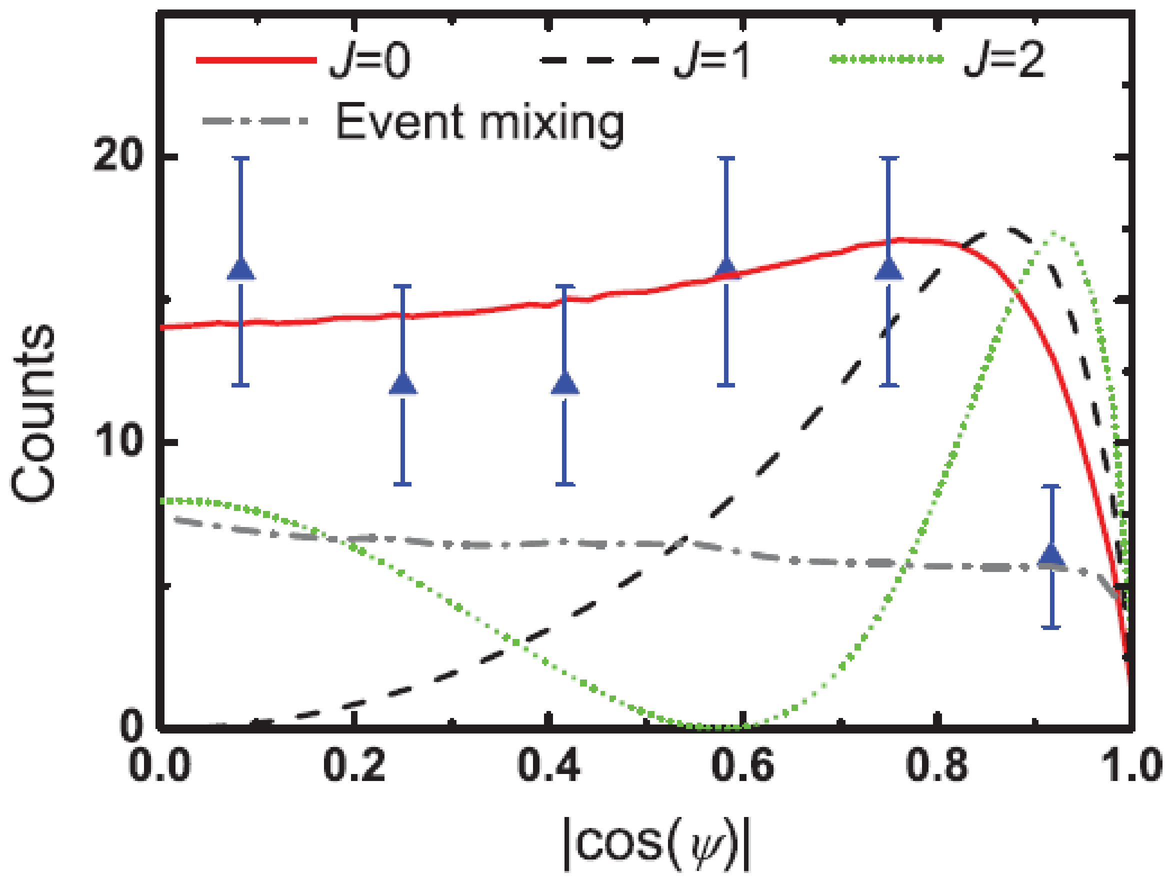




The analysis for 13.6MeV state (^4He+^8He) is consistent with the 4^+ expection. *PRL82(99)383*

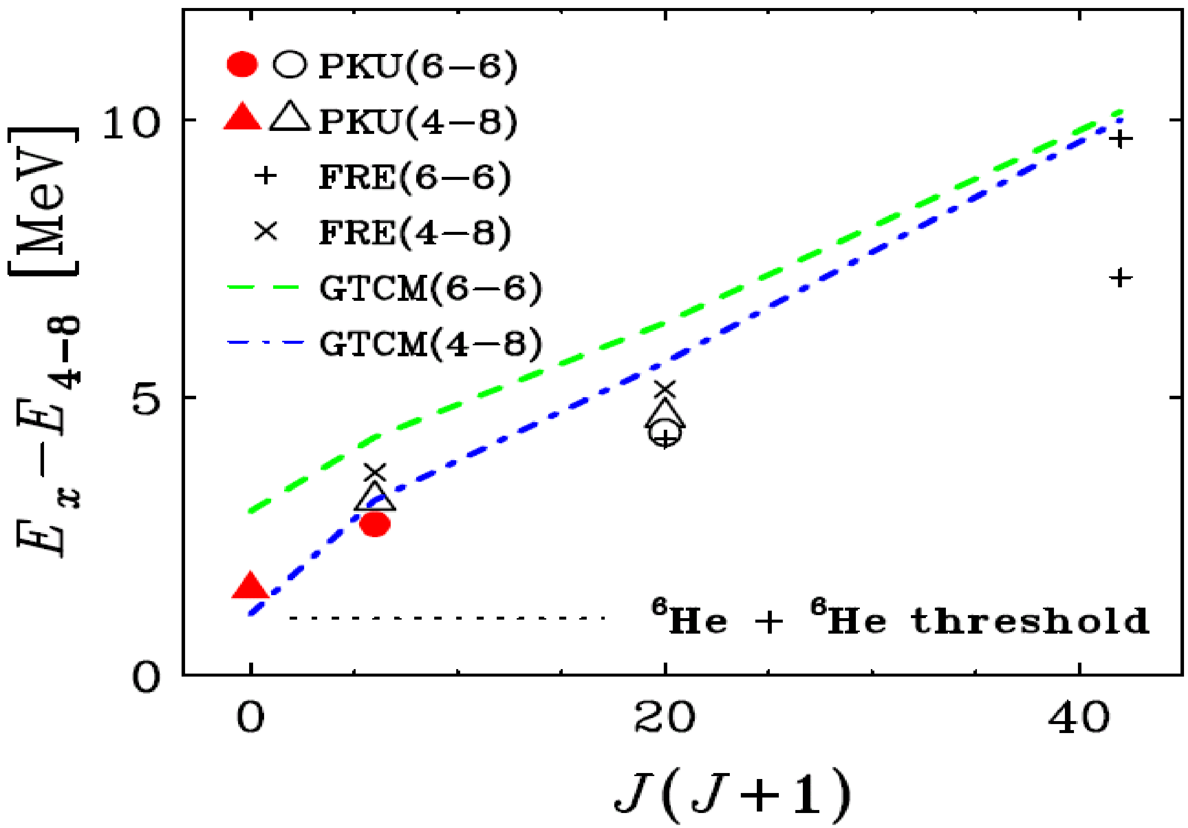
The high sensitivity of this method in the present work can also be demonstrated.

Angular correlation analysis for 10.3 MeV state



The spin-parity of the 10.3MeV state can be definitely determined to be 0^{+}.

Molecular rotational bands



Concl.1#

➢The GTCM calculation reproduces well the ^{4}He+^{8}He band, but overestimates the ^{6}He+^{6}He band by about 1.5 MeV.

Monopole transition matrix M(IS)

- **M(IS) and the Energy weighted sum rule (EWSR)**

$$\mathrm{M}(\mathrm{IS}, 0_1^+ \rightarrow 0_n^+) = < 0_1^+ \,|\, \sum_{i=1}^{A} (\vec{r}_i - \mathrm{R}_{\mathrm{cm}})^2 \,|\, 0_n^+ >$$

$$\mathrm{S}(\mathrm{IS}) = \sum_{\text{all excited } 0_n^+} (E_{x,\mathrm{n}} \,|\, \mathrm{M}(\mathrm{IS}, 0_1^+ \rightarrow 0_n^+) \,|^2) = \frac{2\hbar^2}{m} A R_{rms}^2$$

T. Yamada, PRC 85(12)034315; D J Horsen PRC52(95)1554

- **EWSR_fraction extracted from angular distribution analysis**

➢ Widely used in stable even-even nuclei (e.g ^{12}C,^{16}O,^{40}Ca) and ^{11}B

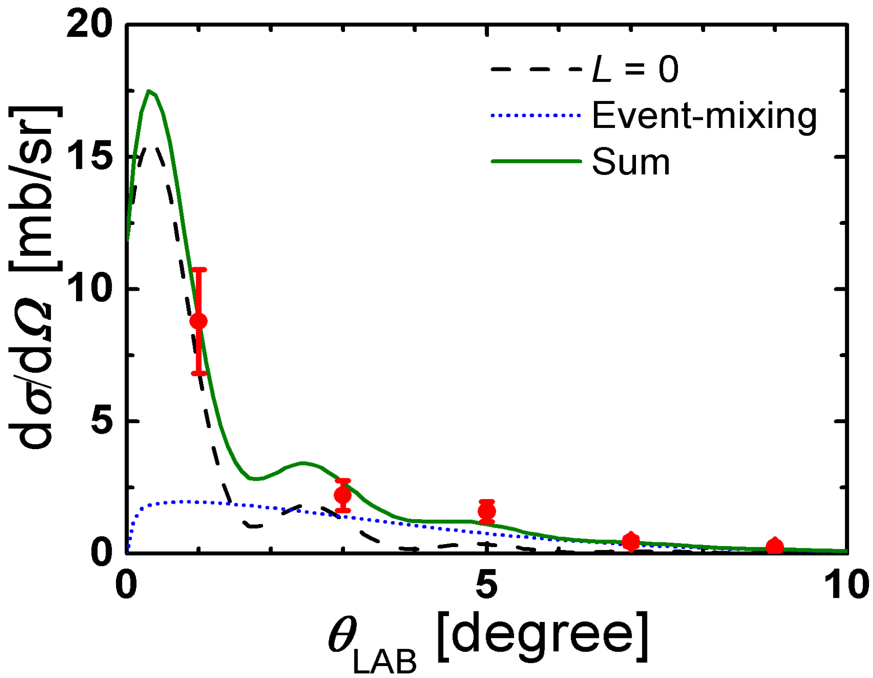
➢ Proper treatment of the background from event-mixing.

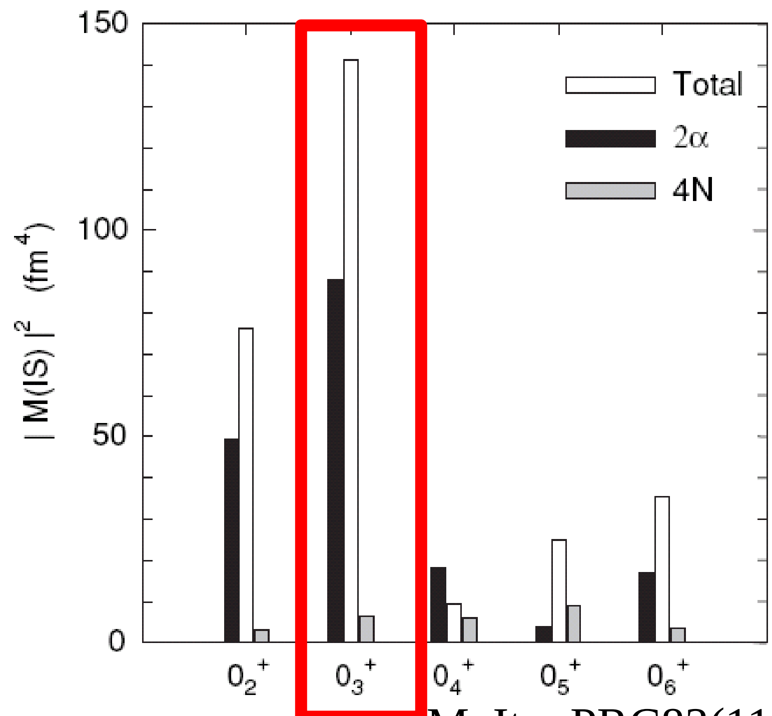
➢ Only L = 0 is taken into account for the current analysis

$$\left(\frac{\mathrm{d}\sigma}{d\Omega}\right)^{\exp} = \sum_L a_L \left(\frac{\mathrm{d}\sigma}{d\Omega}\right)_L^{DWBA} + \left(\frac{\mathrm{d}\sigma}{d\Omega}\right)^{b.g.}$$

- **M(IS):** $|\,\mathrm{M}(\mathrm{IS})\,|^2 * \mathrm{E}_{\mathrm{x}} = S(IS) * EWSR\_fraction$

M(IS) for the 10.3 MeV state **Concl.2#**





M. Ito, PRC83(11)044319

From analysis of the angular distribution, the M(IS) is extracted:
M(IS)=7.0 fm^2 ± 1.0fm^2(stat) ± 0.8 fm^2(sys).

- **Only for the ^{4}He+^{8}He decay channel.
- A strength of ~10 fm^2 is predicted from GTCM calculation with α-4n-α configuration.
- The respective single particle transition strength is ~3fm^2

Spectroscopic analysis with R-matrix

Width

$$\Gamma_{\alpha}(\mathrm{E}) = 2\gamma_{\alpha}{}^{2} P_{l}(\mathrm{E})$$

$\gamma_{\alpha}{}^{2}$ -reduced width

$P_{l}(\mathrm{E})$ – penetrability

$$P_{l}(\mathrm{E}) = \frac{\mathrm{ka}}{\mathrm{F}_{l}(\mathrm{ka})^{2} + \mathrm{G}_{l}(\mathrm{ka})^{2}} \quad (\mathrm{k} = \sqrt{2\mu E_{rel}})$$

$\mathrm{F}_{l}(\mathrm{ka}), \mathrm{G}_{l}(\mathrm{ka})$: regular and irregular colomb functions

Non-dimentional reduced width (Cluster spectroscopic factor)

$$\theta^{2} = \frac{\gamma_{\alpha}{}^{2}}{\gamma_{W}{}^{2}} \qquad \gamma_{W}{}^{2} = \frac{3\hbar^{2}}{2\mu a^{2}} : wigner \ \lim it \qquad (0 \le \theta^{2} \le 1)$$

The (total) width of the 10.3 MeV state is 1.5(2) MeV.

- !!! It's not the cluster decay width.
- Many other decay channels, like neutron emission and gamma transition are also open at Ex~10MeV.

1、From the phase-space calculation, the main decay channel are determined: $^{4}He+^{8}He$, $^{6}He+^{6}He$, $^{11}Be+n$, $^{10}Be+2n$, $^{12}Be+\gamma$

2、The branching ratio for neutron/γ emission channel to $^{10-12}Be$ was determined:

$$\Gamma_{Be}/\Gamma_{tot} = 0.28 \pm 0.12$$

A. A. Korsheninnikov, PLB 343(1995)53

Cluster decay branching ratio: $\Gamma_{He}/\Gamma_{tot} = 1 - \Gamma_{Be}/\Gamma_{tot} = 0.72 \pm 0.12$

Cluster decay width: $\Gamma_{\mathrm{He}} = 1.1(2)\ MeV$

➢Only negligible ^{6}He+^{6}He events are observed(Ex~10MeV).
➢The following discussions are thus restricted to the ^{4}He+^{8}He channel.

Channel radius a: $a = r_0 (A_1^{1/3} + A_2^{1/3}) = 5$ fm, ($r_0 = 1.4$ fm)

➢*a* = 5fm was also suggested from AMD calculation.

Reduced width

$$\gamma_\alpha^2 = \frac{\Gamma_{He}}{2P_0(E_x)} = 0.50(9)\,\text{MeV}$$

Cluster spectroscopic factor

$$\theta_{He}^2 = \frac{\gamma_\alpha^2}{\gamma_W^2} = 0.53(10)$$

Concl.3# Strong clustering

**For the ground state of ^{8}Be (α-α), $\theta_\alpha^2 = 0.45$

Collaborators

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  J.Lee

- ***Valuable discussions with M. Freer and M. Ito***

Summary

1、 An inelastic breakup experiment was carried out at RIBLL to study the cluster structure of ^{12}Be:

- Confirmation of molecular rotational bands.
- Determination of the enhanced Monopole transition matrix for the 10.3 MeV state: M(IS)=7.0fm^2±1.0fm^2
- Determination of the large cluster spectroscopic factor for the 10.3 MeV state: $\theta_{He}{}^2 = 0.53(10)$

The three experimental signals consistently demonstrate the cluster cluster in ^{12}Be.

2、The zero-degree-detection technique developed in this work is demonstrated to be a promising method to measure the monopole transition and explore the cluster formation in unstable nuclei.

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outline

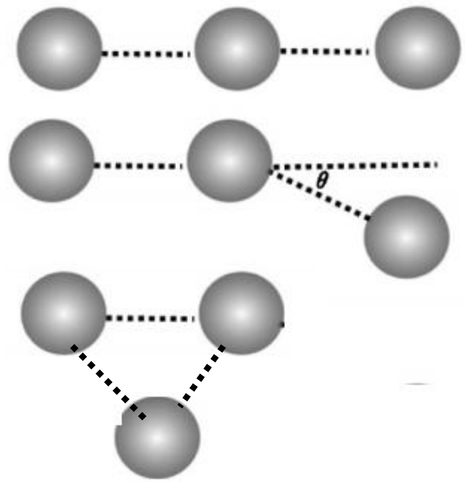
Introduction

The cluster structure of ^{12}Be

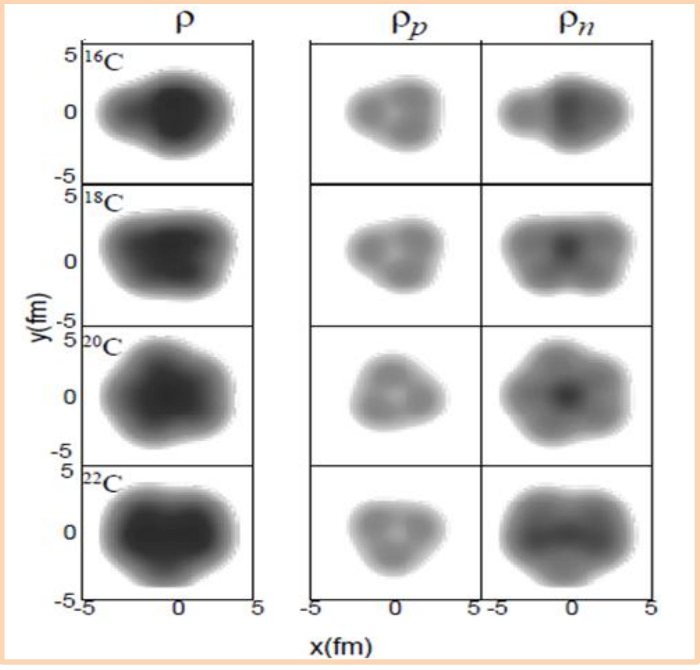
Research plan at RIKEN

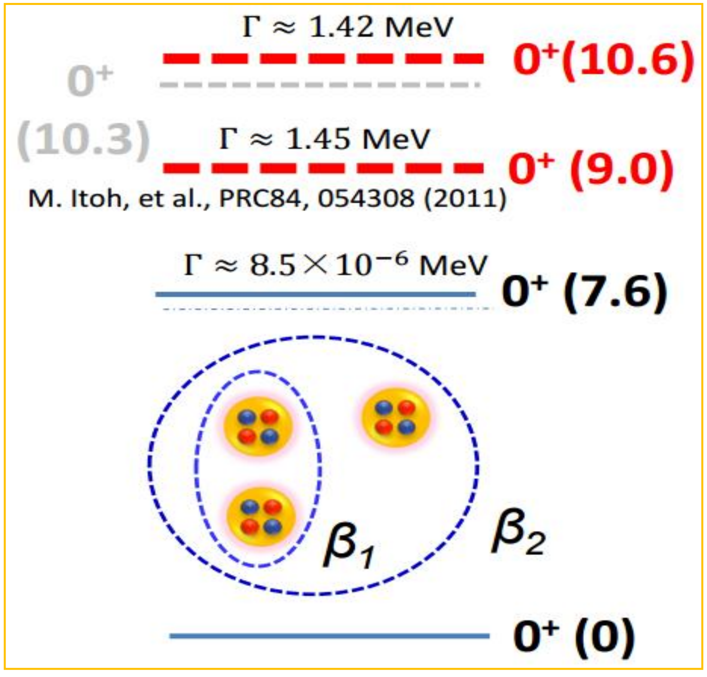
Research plan: α-clustering in C isotopes

- AMD calculations on Carbon isotopes.
- Intensive studies on the Hoyle state
- α-condensation in highly excited states
- Linear Chain states? Bended? Triangle?

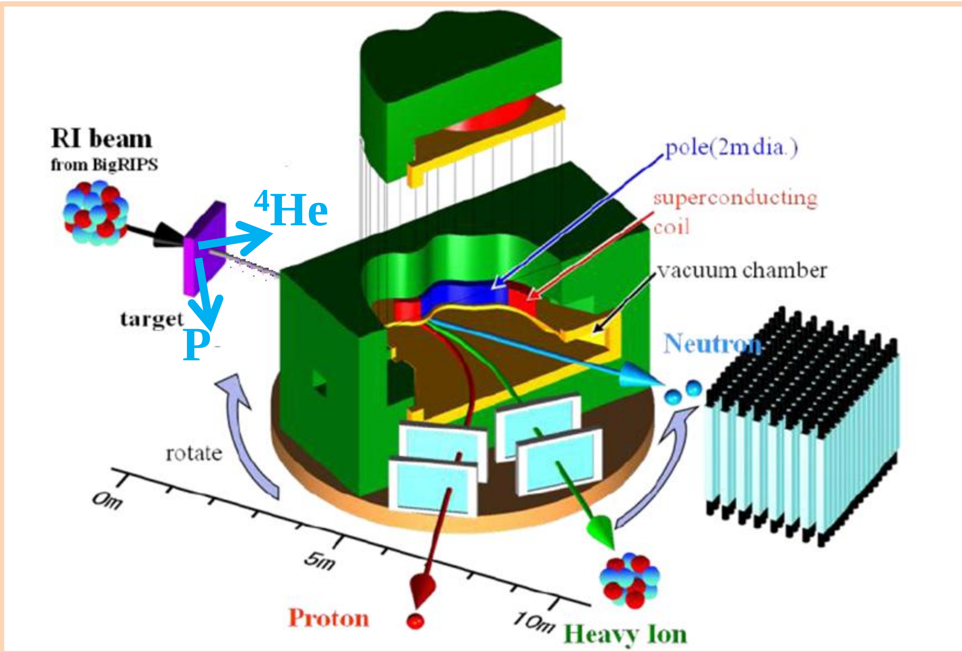


PTPS142(01) 205, PRL 81(98)5291, PRC 86(12)034320, PRL110(13)152502, PRL87(01)192501, PRC 67(03) 051306, PRC69(04)024309, PRC 92(15) 021302(R) , PRC64(01)014301





Measurements with SAMURAI at RIBF



- Solid hydrogen target
- Charged residuals: SAMURAI
- Neutrons: NEBULA (+NeuLAND)
- Cluster fragments: DSSD-CsI(Tl)
- Scattered protons: ESPRI-RPS

Method: Cluster Quasi-Free Scattering

- High-quality intense beams for neutron-rich isotopes at ~150 AMeV.
- Extraction of the α cluster spectroscopic factors from DWIA analysis

Matrix element (from DWIA calculations)

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p} = S_\alpha F_k \sum_\lambda |\mathrm{T}^{L\lambda}|^2 \frac{d^3\sigma}{d\Omega_{p-\alpha}}$$

Free p-α elastic cross section